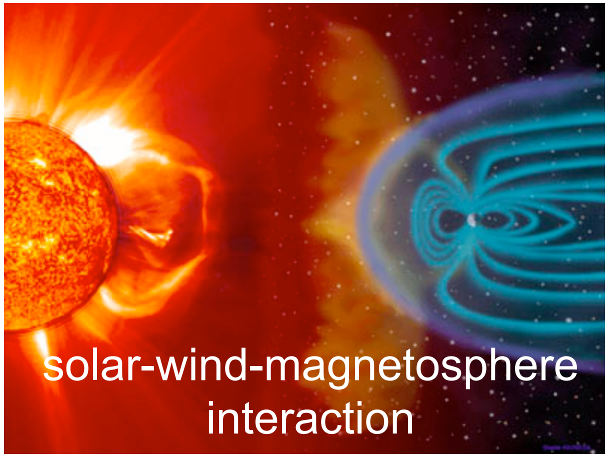
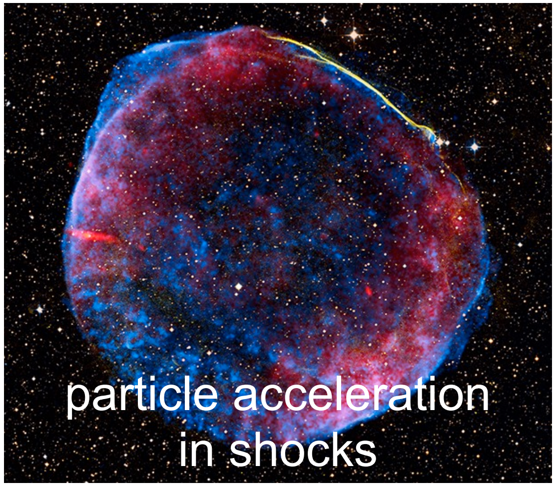
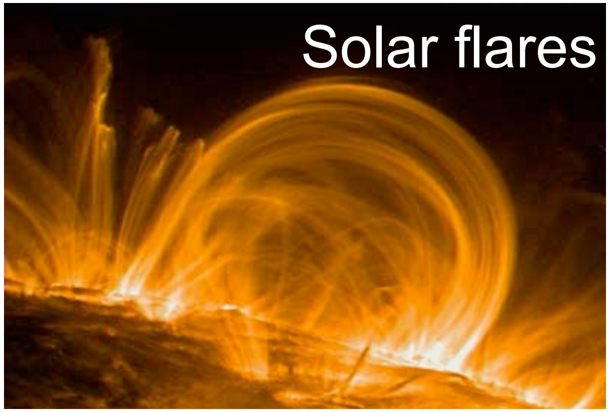
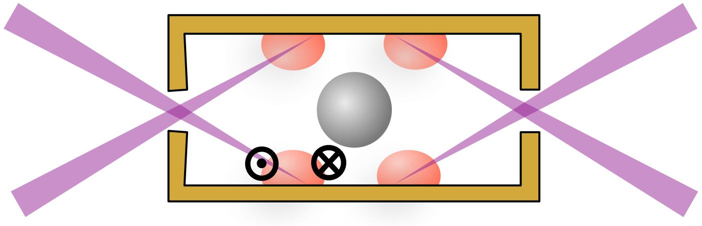
Magnetic Reconnection in low-dissipation, large-system size regimes on the NIF









collision of magnetized plasma bubbles in ICF hohlraums

Collaboration

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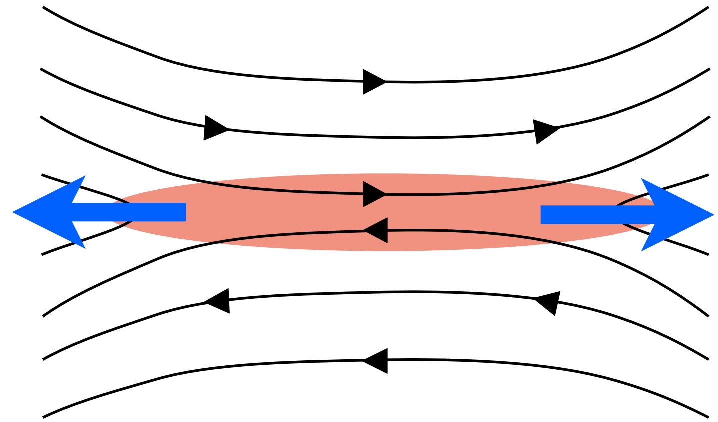
X-ray diagnostics: Marilyn Schneider (LLNL), Ken Hill (PPPL)

Proton radiography: Chikang Li / MIT, L. Gao (PPPL), G. Fiksel (UM)

Particle diagnostics: H. Chen (LLNL), G. Fiksel (UM)

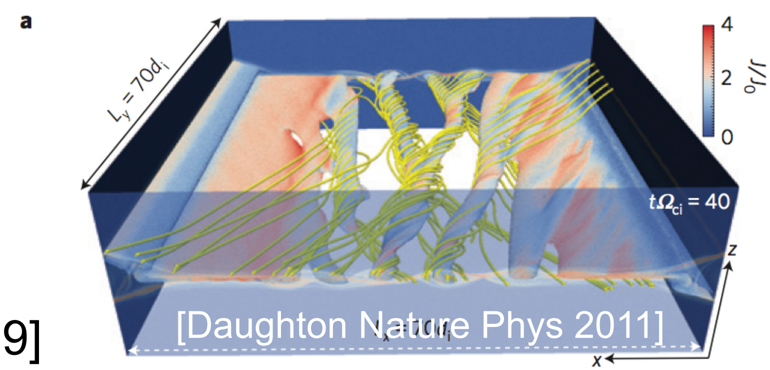
Magnetic reconnection

Magnetic energy stored in reversing magnetic field and released through sling-shot, driven by magnetic forces [Yamada, et al RMP 2010]



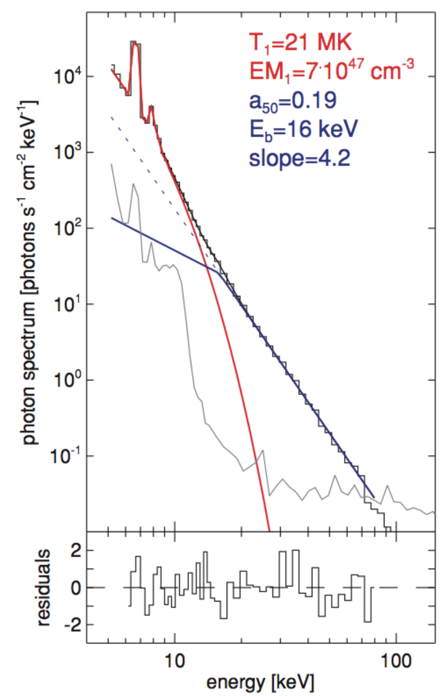
Frontier Physics issues

- Transition from laminar current sheet to multiple island and turbulent reconnection at large system size. [Loureiro 2007, Bhattacharjee 2009]



[Daughton Nature Phys 2011]

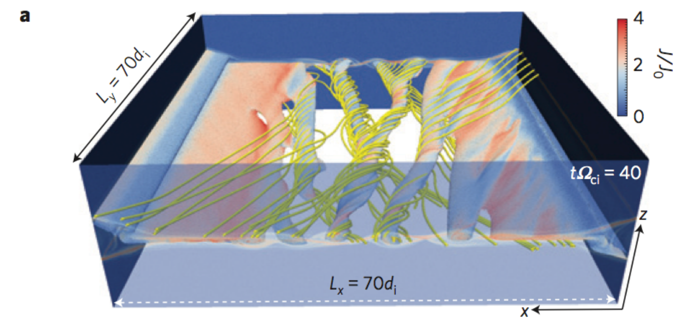
- Particle acceleration by reconnection, efficient generation of power-law tail populations (e.g. solar flares)
  - – direct acceleration along x-lines [e.g. Hoshino 2001]
  - – most-energized particles require "Fermi" acceleration *in multiple island regime.* [Drake et al Nature 2006]



[Krucker ApJ 2010]

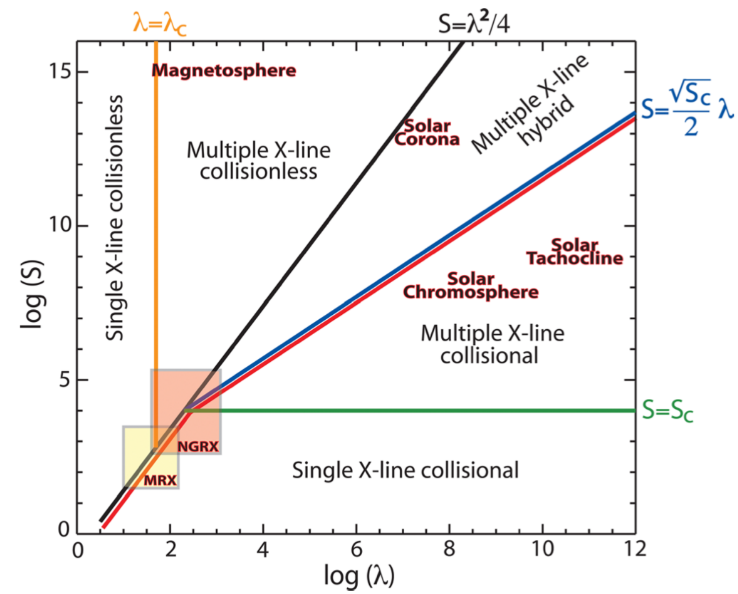
Frontier of reconnection theory and experiment: understanding reconnection physics at large system size and low dissipation

- "Scaling" a reconnection theory or experiment involves much more than just scaling "hydrodynamics" (L,V,t)
- More important (and difficult!) is to scale **plasma dissipation and microphysics**. Parameterized by:
  - Lundquist number $S = \mu_0 L V_A / \eta$
  - Ratio of system size to skin-depth $\lambda = L/d_i$



Plasmoid-unstable current sheet

- Past experimental work has allowed detailed benchmarking of reconnection, but at moderate *S* and *L/di* regimes (see Yamada, Ji, Kulsrud RMP 2010)
- Recent theory breakthroughs demonstrate role of tearing or "plasmoid" instability in large *S* regimes to explain astrophysical reconnection and particle energization.

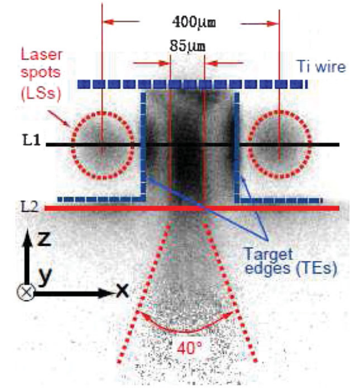


Phase diagram from H. Ji and W. Daughton, PoP (2011).

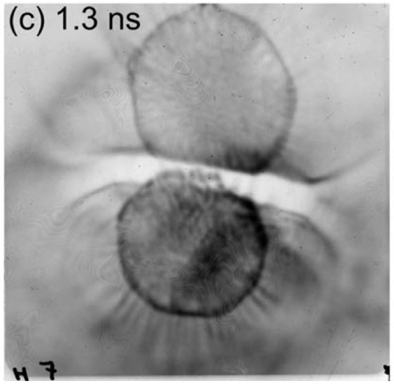
NIF will access deeply into turbulent or multi-x-line regime for the first time

Can we access and study the "multiple island" regime in the laboratory?

- Nominal plasma parameters estimated for NIF should be robustly into the multi-x-line regime
- We propose to directly observe the breakup of current sheet into fractal collection of islands.
    - *2-d* simulations show chains of islands, in principle straightforward to observe. *3-d* is more complicated, we expect to still observe clumpiness. (3-D computation very challenging. c.f. to solar observations)
- Then pursue follow-up questions, e.g. what is scaling of # islands with *L/di* and *S?*
    - Compare to "laminar" or low # island regimes which could be shot on OMEGA EP.
- What is the *reconnection rate* in this regime? Can fast reconnection rates be correlated to multiple islands?
- What is efficiency of *Particle energization?*
    - Do highest energy particles obtain energy from multi-island interactions as predicted in Fermi-acceleration models? [e.g. Drake Nature Phys 2006]



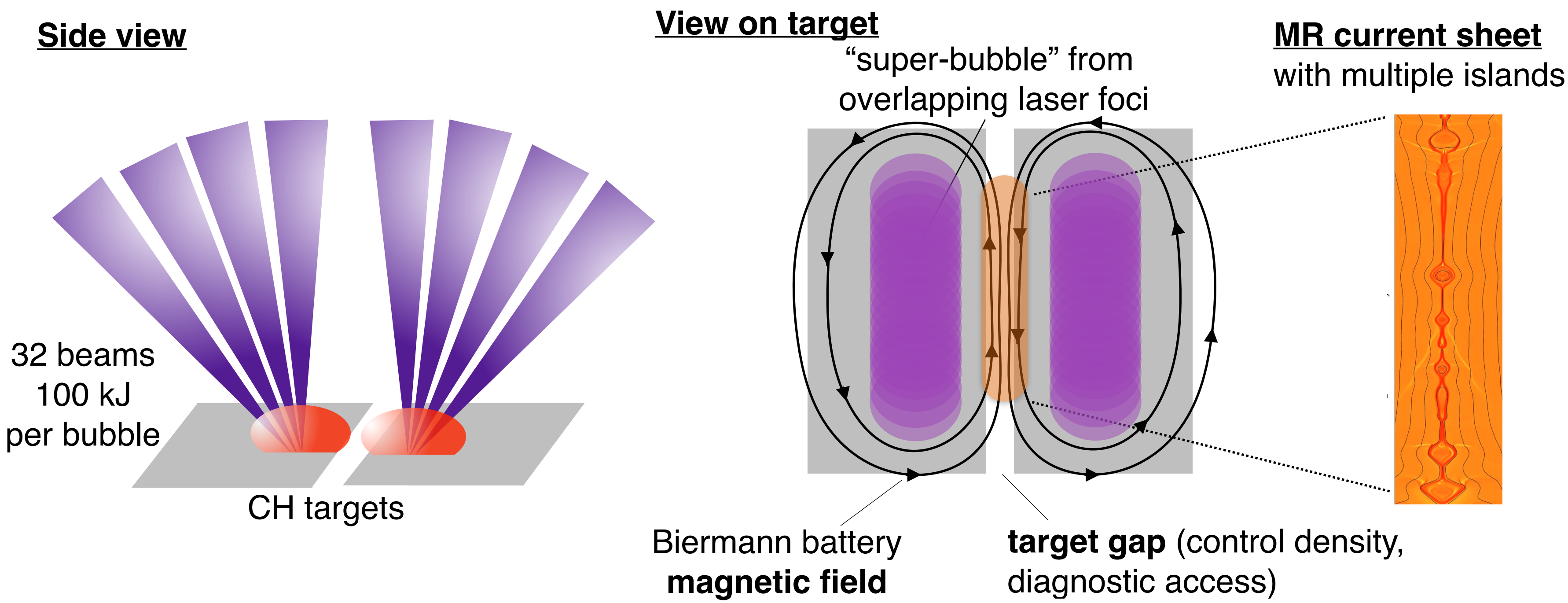
Q.L. Dong, et al, PRL 2012
current sheet in x-rays



(Rosenberg, et al, PRL 2015, no islands observed on OMEGA EP. *Too low S*?)

Development Approach

- Previously successful laser-driven reconnection experiments* are extended to large system size and low dissipation using NIF.
- NIF has ~100x energy per bubble vs previous bubble reconnection experiments. Allows access to much larger size and higher *S*.



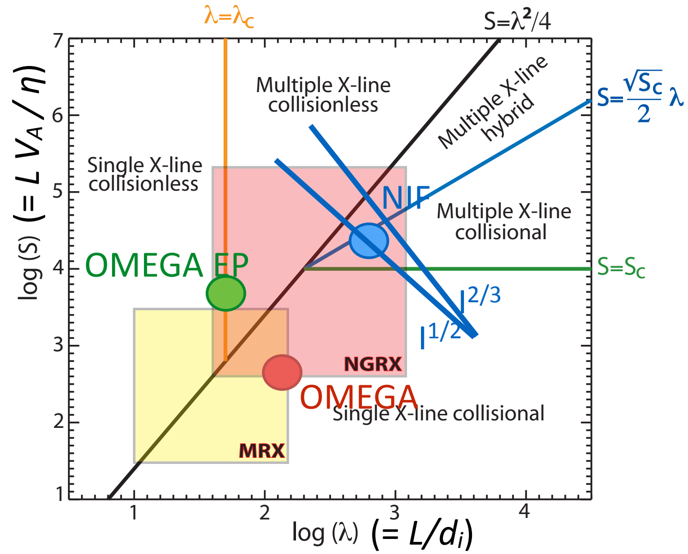
* P.M. Nilson PRL 2006, C.K. Li *et al* PRL 2007, J.Y. Zhong Nature Phys 2011, Q.L. Dong PRL 2012, G. Fiksel *et al* PRL 2014

Proposed plasmas on NIF are predicted to be robustly into multiple-x-line reconnection regimes.

Scaling arguments: Plasma energy directly maps to figures of merit for a reconnection experiment. (*no-free-lunch*)

$$E = nTL^3 \sim S^{0.25} * (\lambda_{mfp}/L)^{0.25} * (L/d_i)^3$$

- NIF Reconnection parameters were established by scaling up from Li et al "OMEGA" reconnection experiments
  - Blue "NIF" curve varies plume length at constant laser energy.
  - n ~ constant,
  - Te ~ Intensity$^{2/3}$ (Atzeni MtV) or Intensity$^{1/2}$ (S.X. Hu PoP 2013)
  - B ~ Te$^{1/2}$, S ~ L B Te$^{3/2}$
- *Significant margins past predicted boundaries of multiple-x-line regime*
- ["OMEGA" is results from Li et al PRL 2007. "EP" from Fiksel PRL 2014]



	OMEGA Li PRL (2007)	NIF design pt (I^0.5 scaling)
Plume length (mm)	0.8	4
Plume width (> 1 mm)	0.8	1
Current sheet length (mm)	2.2	6.5
Energy / bubble (kJ)	0.5	95
Laser time (ns)	1	2.5
Intensity (W/cm^2)	7.8E+13	9.5E+14
Te (eV)	800	2800
B (T)	50	100
S	700	25000
L/di	220	650

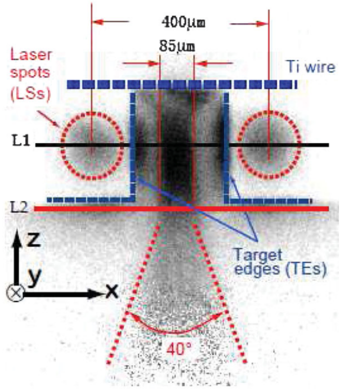
Laser Requirements

- Laser requirements established based on scaling of previous slide.
- Near-term plan is for significant simulation (rad-hydro, PIC, and VFP) to design experiments in more detail

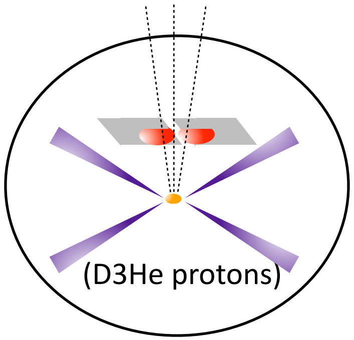
NIF design point	
Energy / bubble (kJ)	**95**
# Beams / bubble	**32**
Laser time (ns)	**2.5**
E / beam (kJ)	**3.00**
Intensity (W/cm^2)	**9.5E+14**
Te (eV)	**2800**

Diagnostic requirements

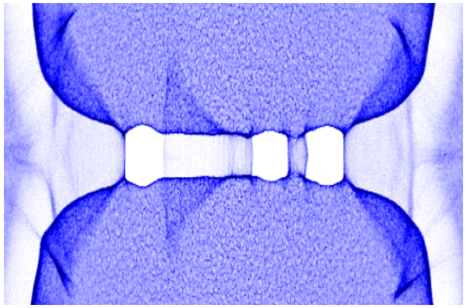
DIM (0,0) view for
protons or x-ray self-emission



- First shots will use **Gated X-ray detector** (GXD) to image the current sheet in X-rays at multiple time points. GXD with Ross filters can be used to constrain Te [T. Ma RSI 2012]



Q.L. Dong, et al, PRL 2012



- Subsequent shots will use **proton radiography** to measure B fields (D3He or NIF ARC).

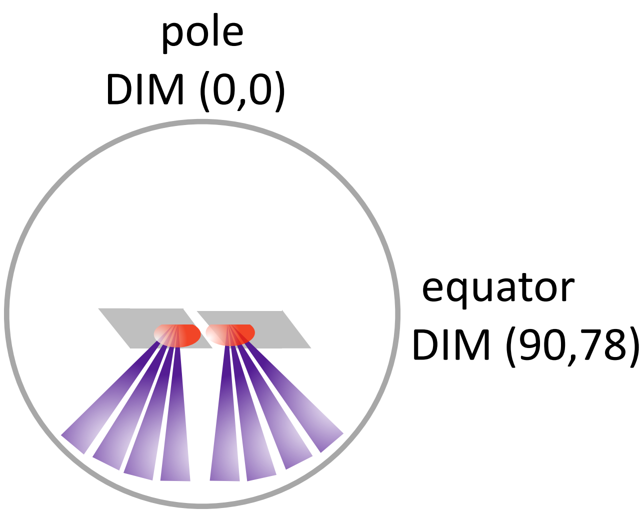
Proof-of-principle, synthetic radiograph from post-processed 2-D PIC simulation showing current sheet with 3 islands. (Smaller scale than NIF)

- **NIF spectrometers** will be used to measure Te based on line ratios of H and He-like dopants (e.g. Ti, Fe)
- **EPPS** will be used to measure energized particles. Ongoing experiments on OMEGA EP on reconnection with external magnetic field have obtained interesting preliminary data.

Target requirements

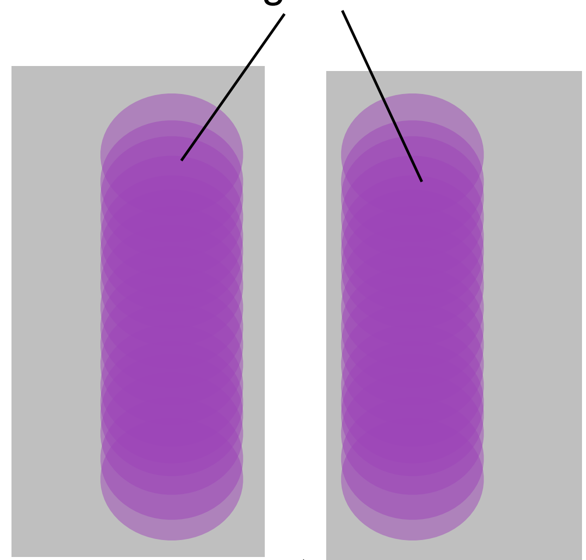
- Proton radiography targets (D3He micro balloons) for P-rad shots
- Flat foil “Magnetic reconnection” target. Simple (in principle). Similar to other direct drive experiments such as ACSEL collisionless shock.

NIF chamber



beams are from lower quads

View on target



Initial shot plan

- We propose 3 shot days with 3-4 shots per day

Day	*Shot*	*Pole*	*Equator*	*Notes*
1 - Observation of plasmoid structures in current sheet	*1*	*GXD*	*GXD*	*GXD images formation of current sheet at 4 time slices. Sets timing for P-rad shots*
	2-3	*P-rad*	*GXD or NXS*	*Follow up with proton radiography based on timing determined from shot 1. Observation of plasmoid structures in CS. Spectrometer will measure Te in current sheet.*
2 - Detailed observations of plasmoids and plasma conditions	*1-3*	*P-Rad*	*GXD or NXS*	*P-rad to continue data set from Day 1. NXS Spectrometer will measure Te in current sheet.*
3 - Particle energization conditions	*1-2*	*EPPS*	*NXS*	*EPPS will measure energized particles from reconnection in x-line direction*
	3-4	*NXS*	*EPPS*	*EPPS will measure energized particles from reconnection in outflow direction*

Near term development plan

- Rad-hydro simulation using DRACO (now with MHD) to obtain plasma parameters relevant to NIF.
- Rad-hydro will be used to calibrate or initialize detailed kinetic simulations (PIC / Fokker-Planck) of reconnection.
- Further experiments on OMEGA EP (using allocated or new proposal) will obtain
  - additional results on field dynamics, reconnection and particle energization under EP conditions.
  - Baseline geometrical tests: Can we successfully *overlap* a few EP beams and generate Biermann fields as we would predict?